THE REGIONAL IMPACTS OF CLIMATE CHANGE

An Assessment of Vulnerability

WMO

Intergovernmental Panel on Climate Change

UNEP

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A Special Report of IPCC Working Group II

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The Regional Impacts of Climate Change: An Assessment of Vulnerability

The degree to which human conditions and the natural environment are vulnerable to the potential effects of climate change is a key concern for governments and the environmental science community worldwide. To provide the best available base of scientific information for policymakers and public use, governments requested that the Intergovernmental Panel on Climate Change (IPCC) prepare this assessment of the vulnerability of different regions of the world. *The Regional Impacts of Climate Change: An Assessment of Vulnerability* reviews state-of-the-art information on potential impacts of climate change for ecological systems, water supply, food production, coastal infrastructure, human health, and other resources for ten global regions:

- Africa
- The Arctic and the Antarctic
- Australasia
- Europe
- Latin America
- Middle East and Arid Asia
- North America
- Small Island States
- Temperate Asia
- Tropical Asia

This assessment reveals that human health, ecological systems, and socioeconomic sectors are vulnerable to changes in climate, including the magnitude and rate of climate change, as well as to changes in climate variability. It also illustrates that the increasing costs of climate and climate variability, in terms of loss of human life and capital due to floods, storms, and droughts, are a result of the lack of adjustment and response in society's policies and use of resources. This book points to management options that would make many sectors more resilient to current variability in climate and thus help these sectors adapt to future changes in climate.

The assessment of each region's vulnerability to climate change shares a common structure to facilitate comparison of information. The focus is on sensitivity, adaptation options, critical zones, and especially vulnerable regions/countries or sectors/resources. The regional assessments have been prepared by leading researchers. The report is based on information contained in the IPCC Second Assessment Report and integrates the most recent research on the topics affecting these regions.

This book can be expected to become the primary source of information on regional aspects of climate change for policymakers, the scientific community, and students.

Robert T. Watson served as co-chair of IPCC Working Group II until September 1997, at which time he assumed the overall chairmanship of the IPCC. He also is Director of the Environment Department of the World Bank. Before taking up his current responsibilities, he was Associate Director for Environment in the Office of Science and Technology Policy, Executive Office of the President of the United States of America. He previously held the positions of Director of the Science Division and Chief Scientist for the Office of Mission to Planet Earth at NASA. He served as Chair of the Science and Technical Advisory Panel to the Global Environmental Facility.

Marufu C. Zinyowera served as co-chair of IPCC Working Group II until September 1997. He has been Director of the Zimbabwe Meteorological Services since 1984, and has represented Zimbabwe in many meteorological and environmental fora.

Richard H. Moss has served as Head of the IPCC Working Group II Technical Support Unit since 1993. Prior to this, he was Deputy Director of the Human Dimensions of Global Environmental Change Programme at the International Geosphere-Biosphere Programme in Stockholm, Sweden. He also served on the faculty of Princeton University, United States.

Foreword

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization and the United Nations Environment Programme in 1988 to assess the scientific and technical literature on climate change, the potential impacts of changes in climate, and options for adaption to and mitigation of climate change. Since its inception, the IPCC has produced a series of Assessment Reports, Special Reports, Technical Papers, methodologies, and other products which have become standard works of reference, widely used by policymakers, scientists, and other experts.

This Special Report, which has been produced by Working Group II of the IPCC, builds on the Working Group's contribution to the Second Assessment Report (SAR), and incorporates more recent information made available since mid-1995. It has been prepared in response to a request from the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the UN Framework Convention on Climate Change (UNFCCC). It addresses an important question posed by the Conference of the Parties (COP) to the UNFCCC, namely, the degree to which human conditions and the natural environment are vulnerable to the potential effects of climate change. The report establishes a common base of information regarding the potential costs and benefits of climatic change, including the evaluation of uncertainties, to help the COP determine what adaptation and mitigation measures might be justified. The report consists of vulnerability assessments for 10 regions that comprise the Earth's entire land surface and adjoining coastal seas: Africa, Arid Western Asia (including the Middle East), Australasia, Europe, Latin America, North America, the Polar Regions (The Arctic and the Antarctic), Small Island States, Temperate Asia, and Tropical Asia. It also includes several annexes that provide information about climate observations, climate projections, vegetation distribution projections, and socioeconomic trends.

As usual in the IPCC, success in producing this report has depended on the enthusiasm and cooperation of numerous scientists and other experts worldwide. These individuals have given generously of their time, often going beyond reasonable demands of duty. We applaud, admire, and are grateful for their commitment to the IPCC process. We are pleased to note the continuing efforts made by the IPCC to ensure participation of scientists and other experts from the developing countries and countries with economies in transition. Given the regional focus of this report, their participation was especially essential to its successful completion. We also express our thanks to the many governments, including those in the developing regions and regions with economies in transition, that supported these scientists and experts in their work.

We take this opportunity to express our gratitude to the following individuals for nurturing another IPCC report through to completion:

- Professor B. Bolin, the Chairman of the IPCC
- The Co-Chairs of Working Group II, Dr. R.T. Watson (USA) and Dr. M.C. Zinyowera (Zimbabwe)
- The Vice-Chairs of the Working Group, Dr. M. Beniston (Switzerland), Dr. O. Canziani (Argentina), Dr. J. Friaa (Tunisia), Ing. (Mrs.) M. Perdomo (Venezuela), Dr. S.K. Sharma (India), Mr. H. Tsukamoto (Japan), and Professor P. Vellinga (The Netherlands)
- Dr. R.H. Moss, Head of the Technical Support Unit (TSU) of Working Group II, Mr. D.J. Dokken, the Project Administrator, and the other members of the TSU, including Ms. S. MacCracken, Ms. L. Van Wie McGrory, and Ms. F. Ormond
- Dr. N. Sundararaman, the Secretary of the IPCC, and his staff, including Ms. R. Bourgeois, Ms. C. Ettori, and Ms. C. Tanikie.

G.O.P. Obasi

Secretary-General
World Meteorological Organization

Ms. E. Dowdeswell

Executive Director
United Nations Environment Programme

Preface

The Intergovernmental Panel on Climate Change (IPCC) has produced a series of Assessment Reports, Special Reports, Technical Papers, and methodologies. As an intergovernmental body, the IPCC has procedures governing the production of each of these. This Special Report on the Regional Impacts of Climate Change was first requested by the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) as a Technical Paper, which restricted the authors to using only materials already in IPCC Assessment Reports and Special Reports. In the course of drafting the paper, the authors felt that the inclusion of new literature that had become available since the completion of the IPCC Second Assessment Report (SAR), including work undertaken under the auspices of several "country studies programs," would make the paper more complete, up-to-date, and broadly representative of trends and vulnerabilities in the regions. Including these materials in the report would not have conformed to the IPCC procedures for Technical Papers; hence, the IPCC decided at its Twelfth Session (Mexico City, 11–13 September 1996) to rewrite the Technical Paper as a Special Report, and SBSTA was informed accordingly.

The Special Report explores the potential consequences of changes in climate for ten continental- or subcontinental-scale regions. Because of the uncertainties associated with regional projections of climate change, the report necessarily takes the approach of assessing sensitivities and vulnerabilities of each region, rather than attempting to provide quantitative predictions of the impacts of climate change. As in the SAR, "vulnerability" is the extent to which climate change may damage or harm a system; it is a function of both sensitivity to climate and the ability to adapt to new conditions.

This assessment confirms the findings of the SAR and underlines the potential for climate change to alter the ability of the Earth's physical and biological systems (land, atmosphere, and oceans) to provide goods and services essential for sustainable economic development.

The report represents an important step in the evolution of the impact assessment process for the IPCC. Previous impact assessments have examined the potential effects of climate change primarily at a global scale. This report analyzes impacts at a continental or subcontinental scale that is of more practical interest to decisionmakers. This regional approach reveals wide variation in the vulnerability of different populations and environmental systems. This variation stems from differences in local environmental conditions; economic, social, and political conditions; and degrees of dependence on climate-sensitive resources, among other factors. Because of its smaller scale of analysis, the report provides more information regarding the potential for the adaptation of systems, activities, and infrastructure to climate change than did the SAR. The chapters indicate, however, that far more research and analysis of adaptation options and adjustment processes are necessary if private sector and governmental entities are to make climate-sensitive sectors more resilient to today's climate variability, and to limit damage from—or take advantage of—potential long-term changes in climate.

The report is also an initial step in examining how projected changes in climate could interact with other environmental changes (e.g., biodiversity loss, land degradation, stratospheric ozone depletion, and degradation of water resources) and social trends (e.g., population growth, economic development, and technological progress). The assessment indicates that additional research into the interlinkages among environmental issues also is needed.

This report will provide a foundation for impacts assessment in the Third Assessment Report (TAR), which is expected to be completed in late 2000. An important early step in the process of preparing the IPCC TAR will be to review and refine the approach—and the regional groupings—used in this assessment. In doing so, advances in the ability to project climatic and environmental changes on finer scales will be an important consideration. The report provides a foundation for the TAR in another important respect, as it represents a substantial further step forward in increasing the level of participation of scientists and technical experts from developing countries and countries with economies in transition. The IPCC remains committed to building on this accomplishment, and will not relax its efforts to identify experts from these regions and secure their participation in future assessments.

Acknowledgments

We would like to acknowledge the contributions of numerous individuals and organizations to the successful completion of this report. First and foremost, we are grateful for the voluntary efforts of the members of the scientific and technical community who prepared and peer-reviewed the chapters and annexes of the report. These individuals served in several capacities, including Convening Lead Authors, Lead Authors, Contributors/Reviewers, Regional Coordinators, and Sector Contributors (authors of the SAR who extracted regional information from their sector-oriented chapters as starting points for the regional assessments). We also gratefully acknowledge the assistance provided by governments to a number of these lead authors.

All of these contributions would have come to nothing had it not been for the tireless and good-natured efforts of David Jon Dokken, Project Administrator, whose roles and responsibilities

in preparation of this report are too numerous to mention, and without whom the report would not have been assembled in such a timely and efficient fashion. Other members of the Working Group II Technical Support Unit also provided significant help in preparation of the report, including Sandy MacCracken, Laura Van Wie McGrory, and Flo Ormond. The staff of the IPCC Secretariat, including Rudie Bourgeois, Chantal Ettori, and Cecilia Tanikie, provided essential support and welcome advice.

Others who contributed to the report in various analytical and organizational roles and to whom we wish to express our thanks include Tererei Abete, Isabel Alegre, Ron Benioff, Carroll Curtis, Paul Desanker, Robert Dixon and his colleagues at the U.S. Country Studies Program, Roland Fuchs, Christy Goodale, David Gray, Mike Hulme, Jennifer Jenkins, Richard Klein, S.C. Majumdar, Scott Ollinger, Erik Rodenberg, Robert Scholes, Joel Smith, Regina Tannon, David Theobald, and Hassan Virji.

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Contents

SUMMARY FOR POLICYMAKERS

THE REGIONAL IMPACTS OF CLIMATE CHANGE: AN ASSESSMENT OF VULNERABILITY

A Special Report of Working Group II of the Intergovernmental Panel on Climate Change

CONTENTS

1. Scope of the Assessment

This report has been prepared at the request of the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) and its subsidiary bodies (specifically, the Subsidiary Body for Scientific and Technological Advice—SBSTA). The special report provides, on a regional basis, a review of state-of-the-art information on the vulnerability to potential changes in climate of ecological systems, socioeconomic sectors (including agriculture, fisheries, water resources, and human settlements), and human health. The report reviews the sensitivity of these systems as well as options for adaptation. Though this report draws heavily upon the sectoral impact assessments of the Second Assessment Report (SAR), it also draws upon more recent peer-reviewed literature (*inter alia*, country studies programs).

2. Nature of the Issue

Human activities (primarily the burning of fossil fuels and changes in land use and land cover) are increasing the atmospheric concentrations of greenhouse gases, which alter radiative balances and tend to warm the atmosphere, and, in some regions, aerosols—which have an opposite effect on radiative balances and tend to cool the atmosphere. At present, in some locations primarily in the Northern Hemisphere, the cooling effects of aerosols can be large enough to more than offset the warming due to greenhouse gases. Since aerosols do not remain in the atmosphere for long periods and global emissions of their precursors are not projected to increase substantially, aerosols will not offset the global long-term effects of greenhouse gases, which are long-lived. Aerosols can have important consequences for continental-scale patterns of climate change.

These changes in greenhouse gases and aerosols, taken together, are projected to lead to regional and global changes in temperature, precipitation, and other climate variables—resulting in global changes in soil moisture, an increase in global mean sea level, and prospects for more severe extreme high-temperature events, floods, and droughts in some places. Based on the range of sensitivities of climate to changes in the atmospheric concentrations of greenhouse gases (IPCC 1996, WG I) and plausible changes in emissions of greenhouse gases and aerosols (IS92a-f, scenarios that assume no climate policies), climate models project that the mean annual global surface temperature will increase by 1–3.5°C by 2100, that global mean sea level will rise by 15–95 cm, and that changes in the spatial and temporal patterns of precipitation would occur. The average rate of warming probably would be greater than any seen in the past 10,000 years, although the actual annual to decadal rate would include considerable natural variability, and regional changes could differ substantially from the global mean value. These long-term, large-scale, human-induced changes will interact with natural variability on time scales of days to decades [e.g., the El Niño-Southern Oscillation (ENSO) phenomenon] and thus influence social and economic well-being. Possible local climate effects which are due to unexpected events like a climate change-induced change of flow pattern of marine water streams like the Gulf Stream have not been considered, because such changes cannot be predicted with confidence at present.

Scientific studies show that human health, ecological systems, and socioeconomic sectors (e.g., hydrology and water resources, food and fiber production, coastal systems, and human settlements), all of which are vital to sustainable development, are sensitive to changes in climate—including both the magnitude and rate of climate change—as well as to changes in climate variability. Whereas many regions are likely to experience adverse effects of climate change—some of which are potentially irreversible—some effects of climate change are likely to be beneficial. Climate change represents an important additional stress on those systems already affected by increasing resource demands, unsustainable management practices, and pollution, which in many cases may be equal to or greater than those of climate change. These stresses will interact in different ways across regions but can be expected to reduce the ability of some environmental systems to provide, on a sustained basis, key goods and services needed for successful economic and social development, including adequate food, clean air and water, energy, safe shelter, low levels of disease, and employment opportunities. Climate change also will take place in the context of economic development, which may make some groups or countries less vulnerable to climate change—for example, by increasing the resources available for adaptation; those that experience low rates of growth, rapid increases in population, and ecological degradation may become increasingly vulnerable to potential changes.

3. Approach of the Assessment

This report assesses the vulnerability of natural and social systems of major regions of the world to climate change. Vulnerability is defined as the extent to which a natural or social system is susceptible to sustaining damage from climate change. Vulnerability is a function of the sensitivity of a system to changes in climate (the degree to which a system will respond to a given change in climate, including both beneficial and harmful effects) and the ability to adapt the system to changes in climate (the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created, due to a given change in climate). Under this framework, a highly vulnerable system would be one that is highly sensitive to modest changes in climate, where the sensitivity includes the potential for substantial harmful effects, and one for which the ability to adapt is severely constrained.

Because the available studies have not employed a common set of climate scenarios and methods, and because of uncertainties regarding the sensitivities and adaptability of natural and social systems, the assessment of regional vulnerabilities is necessarily qualitative. However, the report provides substantial and indispensable information on what currently is known about vulnerability to climate change.

In a number of instances, quantitative estimates of impacts of climate change are cited in the report. Such estimates are dependent upon the specific assumptions employed regarding future changes in climate, as well as upon the particular methods and models applied in the analyses. To interpret these estimates, it is important to bear in mind that uncertainties regarding the character, magnitude, and rates of future climate change remain. These uncertainties impose limitations on the ability of scientists to project impacts of climate change, particularly at regional and smaller scales.

It is in part because of the uncertainties regarding how climate will change that this report takes the approach of assessing vulnerabilities rather than assessing quantitatively the expected impacts of climate change. The estimates are best interpreted as illustrative of the potential character and approximate magnitudes of impacts that may result from specific scenarios of climate change. They serve as indicators of sensitivities and possible vulnerabilities. Most commonly, the estimates are based upon changes in equilibrium climate that have been simulated to result from an equivalent doubling of carbon dioxide (CO_2) in the atmosphere. Usually the simulations have excluded the effects of aerosols. Increases in global mean temperatures corresponding to these scenarios mostly fall in the range of 2–5°C. To provide a temporal context for these scenarios, the range of projected global mean warming by 2100 is 1–3.5°C accompanied by a mean sea-level rise of 15–95 cm, according to the IPCC Second Assessment Report. General circulation model (GCM) results are used in this analysis to justify the order of magnitude of the changes used in the sensitivity analyses. They are not predictions that climate will change by specific magnitudes in particular countries or regions. The amount of literature available for assessment varies in quantity and quality among the regions.

4. Overview of Regional Vulnerabilities to Global Climate Change

Article 2 of the UNFCCC explicitly acknowledges the importance of natural ecosystems, food production, and sustainable economic development (see Box 1). This report's assessment of regional vulnerability to climate change focuses on ecosystems, hydrology and water resources, food and fiber production, coastal systems, human settlements, human health, and other sectors or systems (including the climate system) important to 10 regions that encompass the Earth's land surface. Wide variation in the vulnerability of similar sectors or systems is to be expected across regions, as a consequence of regional differences in local environmental conditions, preexisting stresses to ecosystems, current resource-use patterns, and the framework of factors affecting decisionmaking—including government policies, prices, preferences, and values. Nonetheless, some general observations, based on information contained in the SAR and synthesized from the regional analyses in this assessment, provide a global context for the assessment of each region's vulnerability.

Box 1. Article 2 of the UNFCCC: Objective

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

4.1. Ecosystems

Ecosystems are of fundamental importance to environmental function and to sustainability, and they provide many goods and services critical to individuals and societies. These goods and services include: (i) providing food, fiber, fodder, shelter, medicines, and energy; (ii) processing and storing carbon and nutrients; (iii) assimilating wastes; (iv) purifying water, regulating water runoff, and moderating floods; (v) building soils and reducing soil degradation; (vi) providing opportunities for recreation and tourism; and (vii) housing the Earth's entire reservoir of genetic and species diversity. In addition, natural ecosystems have cultural, religious, aesthetic, and intrinsic existence values. Changes in climate have the potential to affect the geographic location of ecological systems, the mix of species that they contain, and their ability to provide the wide range of benefits on which societies rely for their continued existence. Ecological systems are intrinsically dynamic and are constantly influenced by climate variability. The primary influence of anthropogenic climate change on ecosystems is expected to be through the rate and magnitude of change in climate means and extremes—climate change is expected to occur at a rapid rate relative to the speed at which ecosystems can adapt and reestablish themselves—and through the direct effects of increased atmospheric CO_2 concentrations, which may increase the productivity and efficiency of water use in some plant species. Secondary effects of climate change involve changes in soil characteristics and disturbance regimes (e.g., fires, pests, and diseases), which would favor some species over others and thus change the species composition of ecosystems.

Based on model simulations of vegetation distribution, which use GCM-based climate scenarios, large shifts of vegetation boundaries into higher latitudes and elevations can be expected. The mix of species within a given vegetation class likely will change. Under equilibrium GCM climate scenarios, large regions show drought-induced declines in vegetation, even when the direct effects of CO_2 fertilization are included. By comparison, under transient climate scenarios—in which trace gases increase slowly over a period of years—the full effects of changes in temperature and precipitation lag the effects of a change in atmospheric composition by a number of decades; hence, the positive effects of CO_2 precede the full effects of changes in climate.

Climate change is projected to occur at a rapid rate relative to the speed at which forest species grow, reproduce, and reestablish themselves (past tree species' migration rates are believed to be on the order of 4–200 km per century). For mid-latitude regions, an average warming of 1–3.5°C over the next 100 years would be equivalent to a poleward shift of the present geographic bands of similar temperatures (or "isotherms") approximately 150–550 km, or an altitude shift of about 150–550 m. Therefore, the species composition of forests is likely to change; in some regions, entire forest types may disappear, while new assemblages of species and hence new ecosystems may be established. As a consequence of possible changes in temperature and water availability under doubled equivalent-CO_2 equilibrium conditions, a substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world likely would undergo major changes in broad vegetation types—with the greatest changes occurring in high latitudes and the least in the tropics. In tropical rangelands, major alterations in productivity and species composition would occur due to altered rainfall amount and seasonality and increased evapotranspiration, although a mean temperature increase alone would not lead to such changes.

Inland aquatic ecosystems will be influenced by climate change through altered water temperatures, flow regimes, water levels, and thawing of permafrost at high latitudes. In lakes and streams, warming would have the greatest biological effects at high latitudes—where biological productivity would increase and lead to expansion of cool-water species' ranges—and at the low-latitude boundaries of cold- and cool-water species ranges, where extinctions would be greatest. Increases in flow variability, particularly the frequency and duration of large floods and droughts, would tend to reduce water quality, biological productivity, and habitat in streams. The geographical distribution of wetlands is likely to shift with changes in temperature and precipitation, with uncertain implications for net greenhouse gas emissions from non-tidal wetlands. Some coastal ecosystems (saltwater marshes, mangrove ecosystems, coastal wetlands, coral reefs, coral atolls, and river deltas) are particularly at risk from climate change and other stresses. Changes in these ecosystems would have major negative effects on freshwater supplies, fisheries, biodiversity, and tourism.

Adaptation options for ecosystems are limited, and their effectiveness is uncertain. Options include establishment of corridors to assist the "migration" of ecosystems, land-use management, plantings, and restoration of degraded areas. Because of the projected rapid rate of change relative to the rate at which species can reestablish themselves, the isolation and fragmentation of many ecosystems, the existence of multiple stresses (e.g., land-use change, pollution), and limited adaptation options, ecosystems (especially forested systems, montane systems, and coral reefs) are vulnerable to climate change.

4.2. Hydrology and Water Resources

Water availability is an essential component of welfare and productivity. Currently, 1.3 billion people do not have access to adequate supplies of safe water, and 2 billion people do not have access to adequate sanitation. Although these people are dispersed throughout the globe—reflecting sub-national variations in water availability and quality—some 19 countries (primarily in the Middle East and north and southern Africa) face such severe shortfalls that they are classified as either water-scarce or water-stressed; this number is expected to roughly double by 2025, in large part because of increases in demand resulting from economic and population growth. For example, most policy makers now recognize drought as a recurrent feature of Africa's climate. However, climate change will further exacerbate the frequency and magnitude of droughts in some places.

Changes in climate could exacerbate periodic and chronic shortfalls of water, particularly in arid and semi-arid areas of the world. Developing countries are highly vulnerable to climate change because many are located in arid and semi-arid regions, and most derive their water resources from single-point systems such as bore holes or isolated reservoirs. These systems, by their nature, are vulnerable because there is no redundancy in the system to provide resources, should the primary supply fail. Also, given the limited technical, financial, and management resources possessed by developing countries, adjusting to shortages and/or implementing adaptation measures will impose a heavy burden on their national economies. There is evidence that flooding is likely to become a larger problem in many temperate and humid regions, requiring adaptations not only to droughts and chronic water shortages but also to floods and associated damages, raising concerns about dam and levee failures.

The impacts of climate change will depend on the baseline condition of the water supply system and the ability of water resources managers to respond not only to climate change but also to population growth and changes in demands, technology, and economic, social, and legislative conditions.

Various approaches are available to reduce the potential vulnerability of water systems to climate change. Options include pricing systems, water efficiency initiatives, engineering and structural improvements to water supply infrastructure, agriculture policies, and urban planning/management. At the national/regional level, priorities include placing greater emphasis on integrated, cross-sectoral water resources management, using river basins as resource management units, and encouraging sound pricing and management practices. Given increasing demands, the prevalence and sensitivity of many simple water management systems to fluctuations in precipitation and runoff, and the considerable time and expense required to implement many adaptation measures, the water resources sector in many regions and countries is vulnerable to potential changes in climate.

4.3. *Food and Fiber Production*

Currently, 800 million people are malnourished; as the world's population increases and incomes in some countries rise, food consumption is expected to double over the next three to four decades. The most recent doubling in food production occurred over a 25-year period and was based on irrigation, chemical inputs, and high-yielding crop varieties. Whether the remarkable gains of the past 25 years will be repeated is uncertain: Problems associated with intensifying production on land already in use (e.g., chemical and biological runoff, waterlogging and salinization of soils, soil erosion and compaction) are becoming increasingly evident. Expanding the amount of land under cultivation (including reducing land deliberately taken out of production to reduce agricultural output) also is an option for increasing total crop production, but it could lead to increases in competition for land and pressure on natural ecosystems, increased agricultural emissions of greenhouse gases, a reduction in natural sinks of carbon, and expansion of agriculture to marginal lands—all of which could undermine the ability to sustainably support increased agricultural production.

Changes in climate will interact with stresses that result from actions to increase agricultural production, affecting crop yields and productivity in different ways, depending on the types of agricultural practices and systems in place. The main direct effects will be through changes in factors such as temperature, precipitation, length of growing season, and timing of extreme or critical threshold events relative to crop development, as well as through changes in atmospheric CO_2 concentration (which may have a beneficial effect on the growth of many crop types). Indirect effects will include potentially detrimental changes in diseases, pests, and weeds, the effects of which have not yet been quantified in most available studies. Evidence continues to support the findings of the IPCC SAR that "global agricultural production could be maintained relative to baseline production" for a growing population under $2xCO_2$ equilibrium climate conditions. In addition, the regional findings of this special report lend support to concerns over the "potential serious consequences" of increased risk of hunger in some regions, particularly the tropics and subtropics. Generally, middle to high latitudes may experience increases in productivity, depending on crop type, growing season, changes in temperature regimes, and the seasonality of precipitation. In the tropics and subtropics—where some crops are near their maximum temperature tolerance and where dryland, nonirrigated agriculture predominates—yields are likely to decrease. The livelihoods of subsistence farmers and pastoral peoples, who make up a large portion of rural populations in some regions, also could be negatively affected. In regions where there is a likelihood of decreased rainfall, agriculture could be significantly affected.

Fisheries and fish production are sensitive to changes in climate and currently are at risk from overfishing, diminishing nursery areas, and extensive inshore and coastal pollution. Globally, marine fisheries production is expected to remain about the same in response to changes in climate; high-latitude freshwater and aquaculture production is likely to increase, assuming that natural climate variability and the structure and strength of ocean currents remain about the same. The principal impacts will be felt at the national and local levels, as centers of production shift. The positive effects of climate change—such as longer growing seasons, lower natural winter mortality, and faster growth rates in higher latitudes—may be offset by negative factors such as changes in established reproductive patterns, migration routes, and ecosystem relationships.

Given the many forces bringing profound changes to the agricultural sector, adaptation options that enhance resilience to current natural climate variability and potential changes in means and extremes and address other concerns (e.g., soil erosion, salinization) offer no- or low-regret options. For example, linking agricultural management to seasonal climate predictions can assist in incremental adaptation, particularly in regions where climate is strongly affected by ENSO conditions. The suitability of these options for different regions varies, in part because of differences in the financial and institutional ability of the private sector and governments in different regions to implement them. Adaptation options include changes in crops and crop varieties, development of new crop varieties, changes in planting schedules and tillage practices, introduction of new biotechnologies, and improved water-management and irrigation systems, which have high capital costs and are limited by availability of water resources. Other options, such as minimum- and reduced-tillage technologies, do not require such extensive capitalization but do require high levels of agricultural training and support.

In regions where agriculture is well adapted to current climate variability and/or where market and institutional factors are in place to redistribute agricultural surpluses to make up for shortfalls, vulnerability to changes in climate means and extremes generally is low. However, in regions where agriculture is unable to cope with existing extremes, where markets and institutions to facilitate redistribution of deficits and surpluses are not in place, and/or where adaptation resources are limited, the vulnerability of the agricultural sector to climate change should be considered high. Other factors also will influence the vulnerability of agricultural production in a particular country or region to climate change—including the extent to which current temperatures or precipitation patterns are close to or exceed tolerance limits for important crops; per capita income; the percentage of economic activity based on agricultural production; and the preexisting condition of the agricultural land base.

4.4. *Coastal Systems*

Coastal zones are characterized by a rich diversity of ecosystems and a great number of socioeconomic activities. Coastal human populations in many countries have been growing at double the national rate of population growth. It is currently estimated that about half of the global population lives in coastal zones, although there is large variation among countries. Changes in climate will affect coastal systems through sea-level rise and an increase in storm-surge hazards and possible changes in the frequency and/or intensity of extreme events.

Coasts in many countries currently face severe sea-level rise problems as a consequence of tectonically and anthropogenically induced subsidence. An estimated 46 million people per year currently are at risk of flooding from storm surges. Climate change will exacerbate these problems, leading to potential impacts on ecosystems and human coastal infrastructure. Large numbers of people also are potentially affected by sea-level rise—for example, tens of millions of people in Bangladesh would be displaced by a 1-m increase (the top of the range of IPCC Working Group I estimates for 2100) in the absence of adaptation measures. A growing number of extremely large cities are located in coastal areas, which means that large amounts of infrastructure may be affected. Although annual protection costs for many nations are relatively modest—about 0.1% of gross domestic product (GDP)—the average annual costs to many small island states total several percent of GDP. For some island nations, the high cost of providing storm-surge protection would make it essentially infeasible, especially given the limited availability of capital for investment.

Beaches, dunes, estuaries, and coastal wetlands adapt naturally and dynamically to changes in prevailing winds and seas, as well as sea-level changes; in areas where infrastructure development is not extensive, planned retreat and accommodation to changes may be possible. It also may be possible to rebuild or relocate capital assets at the end of their design life. In other areas, however, accommodation and planned retreat are not viable options, and protection using hard structures (e.g., dikes, levees, floodwalls, and barriers) and soft structures (e.g., beach nourishment, dune restoration, and wetland creation) will be necessary. Factors that limit the implementation of these options include inadequate financial resources, limited institutional and technological capability, and shortages of trained personnel. In most regions, current coastal management and planning frameworks do not take account of the vulnerability of key systems to changes in climate and sea level or long lead times for implementation of many adaptation measures. Inappropriate policies encourage development in impact-prone areas. Given increasing population density in coastal zones, long lead times for implementation of many adaptation measures, and institutional, financial, and technological limitations (particularly in many developing countries), coastal systems should be considered vulnerable to changes in climate.

4.5. *Human Health*

In much of the world, life expectancy is increasing; in addition, infant and child mortality in most developing countries is dropping. Against this positive backdrop, however, there appears to be a widespread increase in new and resurgent vector-borne and infectious diseases, such as dengue, malaria, hantavirus, and cholera. In addition, the percentage of the developing world's population living in cities is expected to increase from 25% (in 1960) to more than 50% by 2020, with percentages in some regions far exceeding these averages. These changes will bring benefits only if accompanied by increased access to services such as sanitation and potable water supplies; they also can lead to serious urban environmental problems, including air pollution (e.g., particulates, surface ozone, and lead), poor sanitation, and associated problems in water quality and potability, if access to services is not improved.

Climate change could affect human health through increases in heat-stress mortality, tropical vector-borne diseases, urban air pollution problems, and decreases in cold-related illnesses. Compared with the total burden of ill health, these problems are not likely to be large. In the aggregate, however, the direct and indirect impacts of climate change on human health do constitute a hazard to human population health, especially in developing countries in the tropics and subtropics; these impacts have considerable potential to cause significant loss of life, affect communities, and increase health-care costs and lost work days. Model projections (which entail necessary simplifying assumptions) indicate that the geographical zone of potential malaria transmission would expand in response to global mean temperature increases at the upper part of the IPCC-projected range (3–5°C by 2100), increasing the affected proportion of the world's population from approximately 45% to approximately 60% by the latter half of the next century. Areas where malaria is currently endemic could experience intensified transmission (on the order of 50–80 million additional annual cases, relative to an estimated global background total of 500 million cases). Some increases in non-vector-borne infectious diseases—such as salmonellosis, cholera, and giardiasis—also could occur as a result of elevated temperatures and increased flooding. However, quantifying the projected health impacts is difficult because the extent of climate-induced health disorders depends on other factors—such as migration, provision of clean urban environments, improved nutrition, increased availability of potable water, improvements in sanitation, the extent of disease vector-control measures, changes in resistance of vector organisms to insecticides, and more widespread availability of health care. Human health is vulnerable to changes in climate—particularly in urban areas, where access to space conditioning may be limited, as well as in areas where exposure to vector-borne and communicable diseases may increase and health-care delivery and basic services, such as sanitation, are poor.

5. Anticipatory Adaptation in the Context of Current Policies and Conditions

A key message of the regional assessments in this report is that many systems and policies are not well-adjusted even to today's climate and climate variability. Increasing costs, in terms of human life and capital, from floods, storms, and droughts demonstrate current vulnerability. This situation suggests that there are adaptation options that would make many sectors more resilient to today's conditions and thus would help in adapting to future changes in climate. These options—so-called "win-win" or "no-regrets" options—could have multiple benefits and most likely would prove to be beneficial even in the absence of climate change impacts.

In many countries, the economic policies and conditions (e.g., taxes, subsidies, and regulations) that shape private decision making, development strategies, and resource-use patterns (and hence environmental conditions) hinder implementation of adaptation measures. In many countries, for example, water is subsidized, encouraging over-use (which draws down existing sources) and discouraging conservation measures—which may well be elements of future adaptation strategies. Other examples are inappropriate land-use zoning and/or subsidized disaster insurance, which encourage infrastructure development in areas prone to flooding or other natural disasters—areas that could become even more vulnerable as a result of climate change. Adaptation and better incorporation of the long-term environmental consequences of resource use can be brought about through a range of approaches, including strengthening legal and institutional frameworks, removing preexisting market distortions (e.g., subsidies), correcting market failures (e.g., failure to reflect environmental damage or resource depletion in prices or inadequate economic valuation of biodiversity), and promoting public participation and education. These types of actions would adjust resource-use patterns to current environmental conditions and better prepare systems for potential future changes.

The challenge is to identify opportunities that facilitate sustainable development by making use of existing technologies and developing policies that make climate-sensitive sectors resilient to today's climate variability. This strategy will require many regions of the world to have more access to appropriate technologies, information, and adequate financing. In addition, the regional assessments suggest that adaptation will require anticipation and planning; failure to prepare systems for projected changes in climate means, variability, and extremes could lead to capital-intensive development of infrastructure or technologies that are ill-suited to future conditions, as well as missed opportunities to lower the costs of adaptation. Additional analysis of current vulnerability to today's climate fluctuations and existing coping mechanisms is needed and will offer lessons for the design of effective options for adapting to potential future changes in climate.

6. Regional Vulnerability to Global Climate Change

6.1. Africa

Several climate regimes characterize the African continent; the wet tropical, dry tropical, and alternating wet and dry climates are the most common. Many countries on the continent are prone to recurrent droughts; some drought episodes, particularly in southeast Africa, are associated with ENSO phenomena. Deterioration in terms of trade, inappropriate policies, high population growth rates, and lack of significant investment—coupled with a highly variable climate—have made it difficult for several countries to develop patterns of livelihood that would reduce pressure on the natural resource base. Under the assumption that access to adequate financing is not provided, Africa is the continent most vulnerable to the impacts of projected changes because widespread poverty limits adaptation capabilities.

Ecosystems: In Africa today, tropical forests and rangelands are under threat from population pressures and systems of land use. Generally apparent effects of these threats include loss of biodiversity, rapid deterioration in land cover, and depletion of water availability through destruction of catchments and aquifers. Changes in climate will interact with these underlying changes in the environment, adding further stresses to a deteriorating situation. A sustained increase in mean ambient temperatures beyond 1°C would cause significant changes in forest and rangeland cover; species distribution, composition, and migration patterns; and biome distribution. Many organisms in the deserts already are near their tolerance limits, and some may not be able to adapt further under hotter conditions. Arid to semi-arid subregions and the grassland areas of eastern and southern Africa, as well as areas currently under threat from land degradation and desertification, are particularly vulnerable. Were rainfall to increase as projected by some GCMs in the highlands of east Africa and equatorial central Africa, marginal lands would become more productive than they are now. These effects are likely to be negated, however, by population pressure on marginal forests and rangelands. Adaptive options include control of deforestation, improved rangeland management, expansion of protected areas, and sustainable management of forests.

Hydrology and Water Resources: Of the 19 countries around the world currently classified as water-stressed, more are in Africa than in any other region—and this number is likely to increase, independent of climate change, as a result of increases in demand resulting from population growth, degradation of watersheds caused by land-use change, and siltation of river basins. A reduction in precipitation projected by some GCMs for the Sahel and southern Africa—if accompanied by high inter-annual variability—could be detrimental to the hydrological balance of the continent and disrupt various water-dependent socioeconomic activities. Variable climatic conditions may render the management of water resources more difficult both within and between countries. A drop in water level in dams and rivers could adversely affect the quality of water by increasing the concentrations of sewage waste and industrial effluents, thereby increasing the potential for the outbreak of diseases and reducing the quality and quantity of fresh water available for domestic use. Adaptation options include water harvesting, management of water outflow from dams, and more efficient water usage.

Agriculture and Food Security: Except in the oil-exporting countries, agriculture is the economic mainstay in most African countries, contributing 20–30% of GDP in sub-Saharan Africa and 55% of the total value of African exports. In most African countries, farming depends entirely on the quality of the rainy season—a situation that makes Africa particularly vulnerable to climate change. Increased droughts could seriously impact the availability of food, as in the horn of Africa and southern Africa during the 1980s and 1990s. A rise in mean winter temperatures also would be detrimental to the production of winter wheat and fruits that need the winter chill. However, in subtropical Africa, warmer winters would reduce the incidence of damaging frosts, making it possible to grow horticultural produce susceptible to frosts at higher elevations than is possible at present. Productivity of freshwater fisheries may increase, although the mix of fish species could be altered. Changes in ocean dynamics could lead to changes in the migratory patterns of fish and possibly to reduced fish landings, especially in coastal artisinal fisheries.

Coastal Systems: Several African coastal zones—many of which already are under stress from population pressure and conflicting uses—would be adversely affected by sea-level rise associated with climate change. The coastal nations of west and central Africa (e.g., Senegal, Gambia, Sierra Leone, Nigeria, Cameroon, Gabon, Angola) have low-lying lagoonal coasts that are susceptible to erosion and hence are threatened by sea-level rise, particularly because most of the countries in this area have major and rapidly expanding cities on the coast. The west coast often is buffeted by storm surges and currently is at risk from erosion, inundation, and extreme storm events. The coastal zone of east Africa also will be affected, although this area experiences calm conditions through much of the year. However, sea-level rise and climatic variation may reduce the buffer effect of coral and patch reefs along the east coast, increasing the potential for erosion. A number of studies indicate that a sizable proportion of the northern part of the Nile delta will be lost through a combination of inundation and erosion, with consequent loss of agricultural land and urban areas. Adaptation measures in African coastal zones are available but would be very costly, as a percentage of GDP, for many countries. These measures could include erection of sea walls and relocation of vulnerable human settlements and other socioeconomic facilities.

Human Settlement, Industry, and Transportation: The main challenges likely to face African populations will emanate from extreme climate events such as floods (and resulting landslides in some areas), strong winds, droughts, and tidal waves. Individuals living in marginal areas may be forced to migrate to urban areas (where infrastructure already is approaching its limits as a result of population pressure) if the marginal lands become less productive under new climate conditions. Climate change could worsen current trends in depletion of biomass energy resources. Reduced stream flows would cause reductions in hydropower production, leading to negative effects on industrial productivity and costly relocation of some industrial plants. Management of pollution, sanitation, waste disposal, water supply, and public health, as well as provision of adequate infrastructure in urban areas, could become more difficult and costly under changed climate conditions.

Human Health: Africa is expected to be at risk primarily from increased incidences of vector-borne diseases and reduced nutritional status. A warmer environment could open up new areas for malaria; altered temperature and rainfall patterns also could increase the incidence of yellow fever, dengue fever, onchocerciasis, and trypanosomiasis. Increased morbidity and mortality in subregions where vector-borne diseases increase following climatic changes would have far-reaching economic consequences. In view of the poor economic status of most African nations, global efforts will be necessary to tackle the potential health effects.

Tourism and Wildlife: Tourism—one of Africa's fastest-growing industries—is based on wildlife, nature reserves, coastal resorts, and an abundant water supply for recreation. Projected droughts and/or reduction in precipitation in the Sahel and eastern and southern Africa would devastate wildlife and reduce the attractiveness of some nature reserves, thereby reducing income from current vast investments in tourism.

Conclusions: The African continent is particularly vulnerable to the impacts of climate change because of factors such as widespread poverty, recurrent droughts, inequitable land distribution, and overdependence on rain-fed agriculture. Although adaptation options, including traditional coping strategies, theoretically are available, in practice the human, infrastructural, and economic response capacity to effect timely response actions may well be beyond the economic means of some countries.

6.2. Polar Regions: The Arctic and the Antarctic

The polar regions include some very diverse landscapes, and the Arctic and the Antarctic are very different in character. The Arctic is defined here as the area within the Arctic Circle; the Antarctic here includes the area within the Antarctic Convergence, including the Antarctic continent, the Southern Ocean, and the sub-Antarctic islands. The Arctic can be described as a frozen ocean surrounded by land, and the Antarctic as a frozen continent surrounded by ocean. The projected warming in the polar regions is greater than for many other regions of the world. Where temperatures are close to freezing on average, global warming will reduce land ice and sea ice, the former contributing to sea-level rise. However, in the interiors of ice caps, increased temperature may not be sufficient to lead to melting of ice and snow, and will tend to have the effect of increasing snow accumulation.

Ecosystems: Major physical and ecological changes are expected in the Arctic. Frozen areas close to the freezing point will thaw and undergo substantial changes with warming. Substantial loss of sea ice is expected in the Arctic Ocean. As warming occurs, there will be considerable thawing of permafrost—leading to changes in drainage, increased slumping, and altered landscapes over large areas. Polar warming probably will increase biological production but may lead to different species composition on land and in the sea. On land, there